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Prospects for Precision Neutrino Cross Section Measurements

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NuFact 2015

CBPF, Rio de Janeiro

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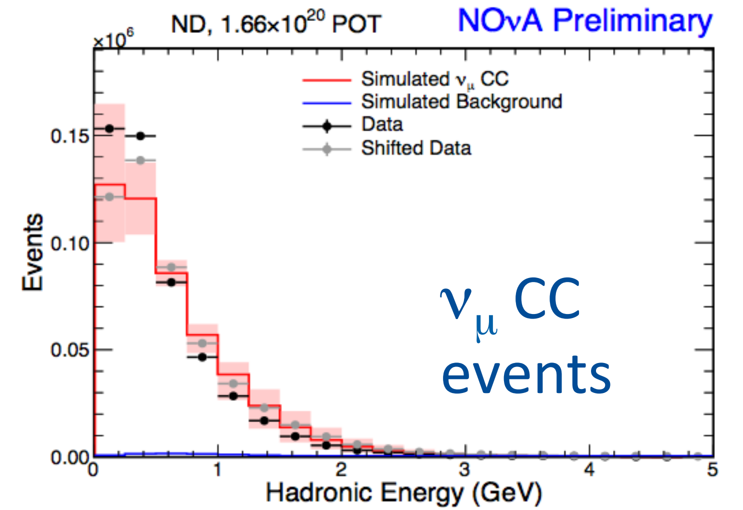
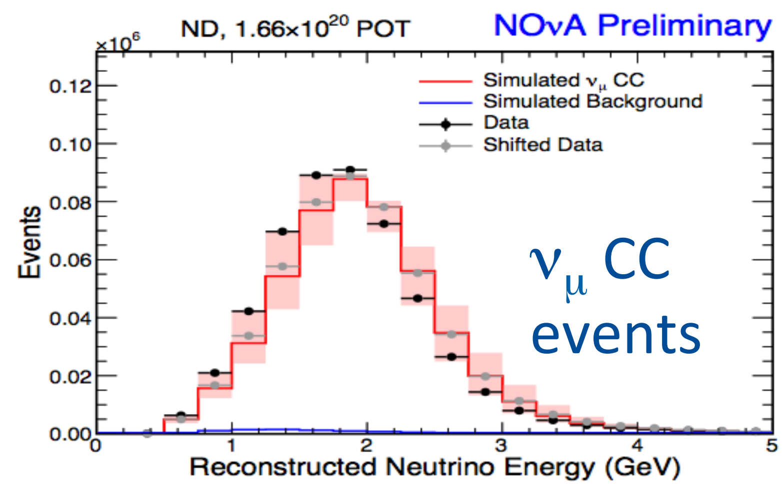
Why Precision Cross Sections?

- Understand more about how neutrinos interact with p,n
- Understand more about the nuclear environment
  - e- scattering, but with fewer events, harder energy reconstruction, and higher flux uncertainties
- To help provide input for Oscillation Experiments
  - Example at right: NOvA sees difference in hadron and neutrino energies: why?





R. Patterson, FNAL JETP 8/15

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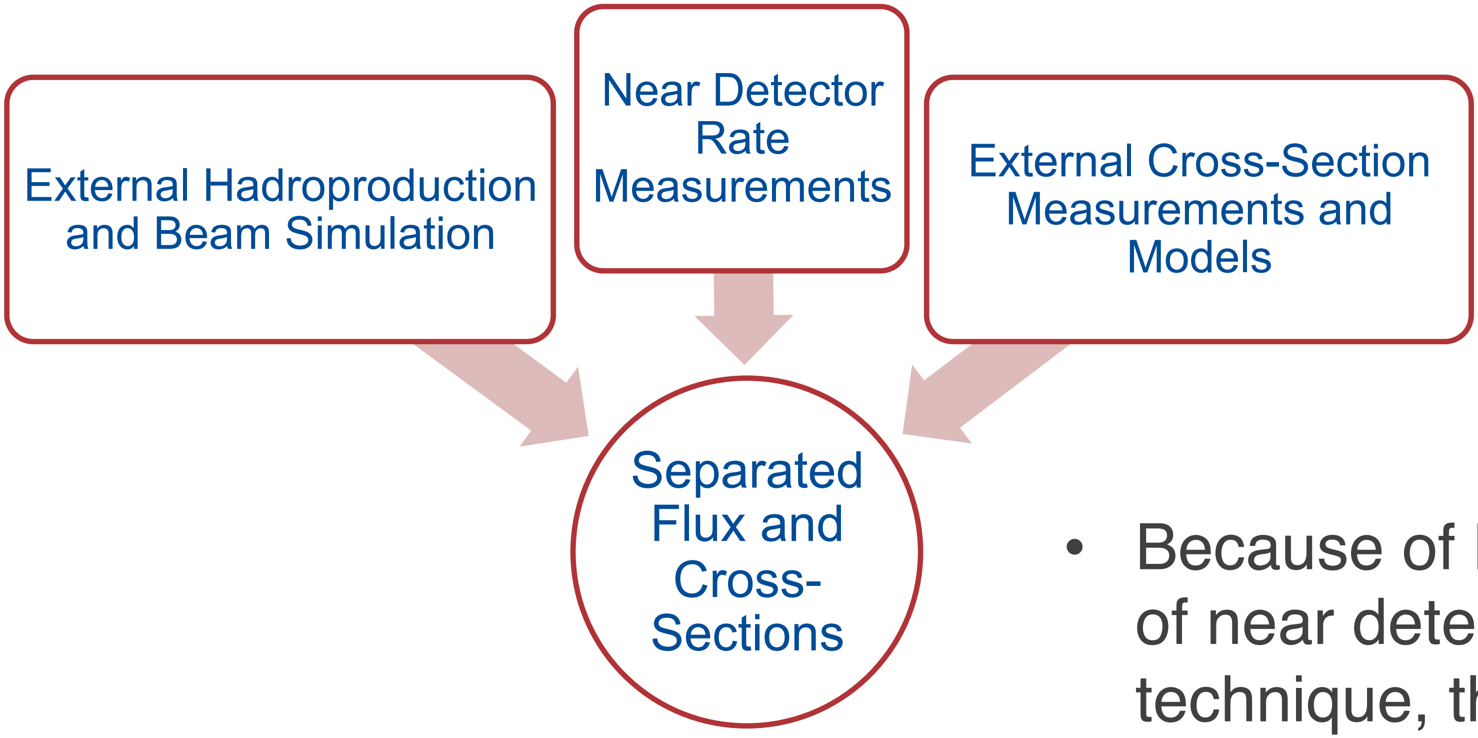
How external cross section measurements help?

- Experiments have a more or less universal scheme for using the near detector data to get flux and cross-section



- Because of limitations of near detector technique, these rely on accurate models

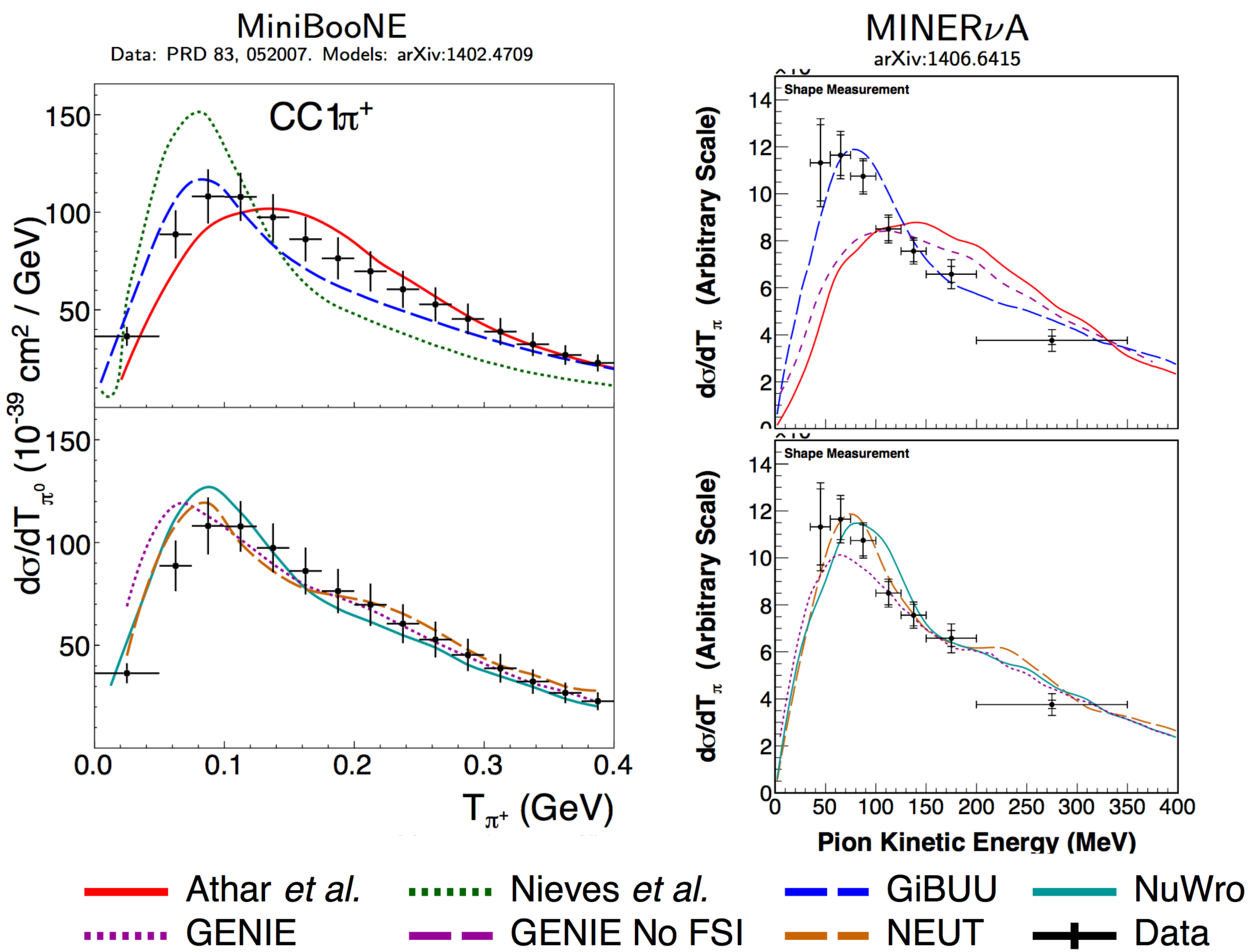
Graphic courtesy K. McFarland

What does precision mean?

- What tests a model better:
  - A 1% measurement of the absolute neutrino quasi-elastic cross section on your favorite nucleus as a function of your favorite kinematic variable?
  - 10 measurements of 10% precision on a broad range of
    - Interaction channels
    - Neutrino energies
    - Target nuclei
  - You be the judge…

Example: Inclusive pion production on Carbon

- Important signal process for NOvA
- Background for T2K, process
- Very sensitive to effects of nucleus
- Models tested with 15-20% differential measurements by comparing across energy



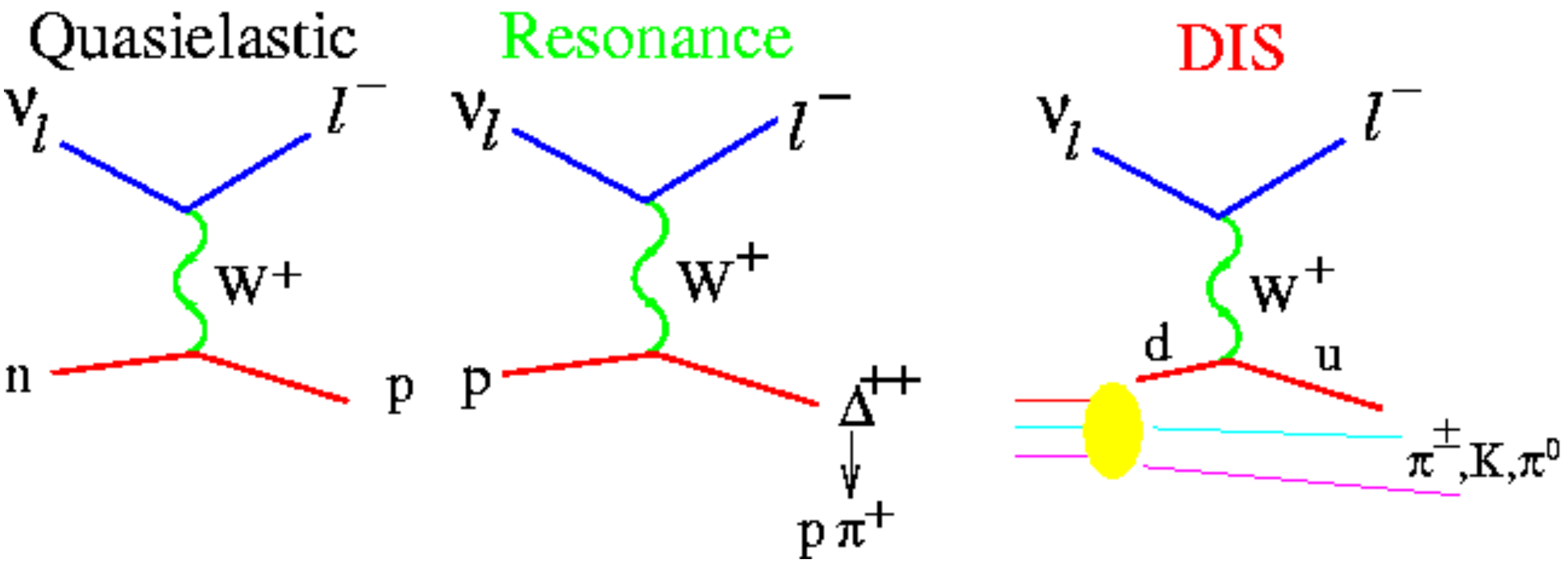
from P. Rodrigues, WINP

On the road to precision…

- Broad Range of Neutrino Energies
  – To get to broad range of interaction channels
- Broad Range of Target Nuclei
  – To constrain both the nucleon-level processes and the role of the nucleus in what actually enters the detector
- Capable detectors
  – Low thresholds, good particle ID needed
- Capable Beamlines
  – Provide the statistics: but need good flux constraints too!

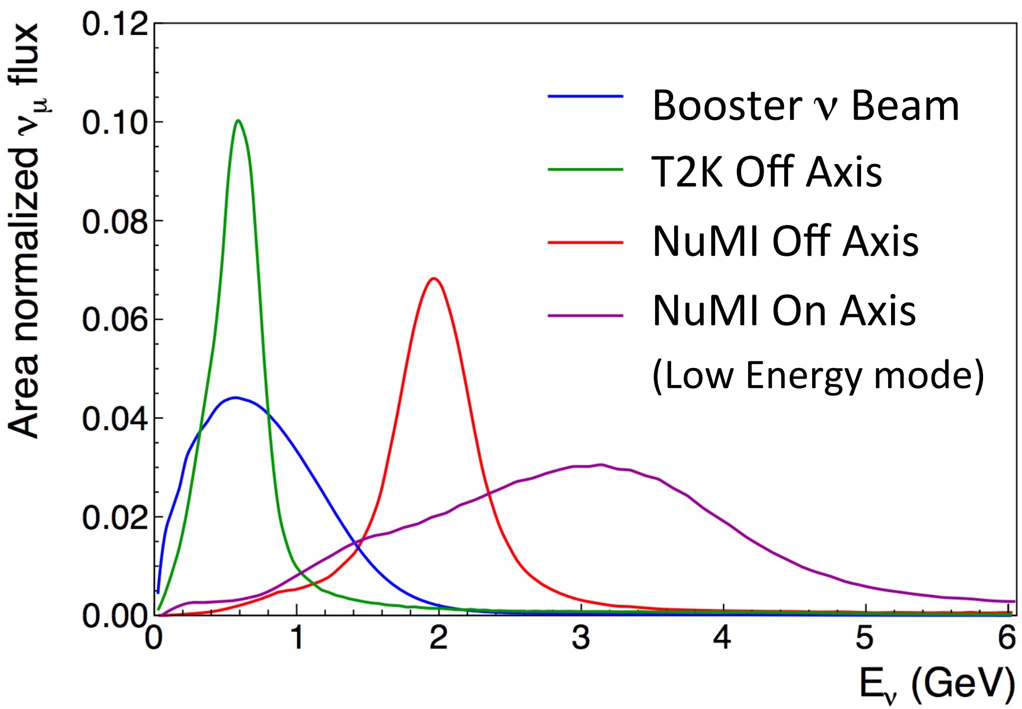
Need to study broad range of neutrino interactions

- This means a broad range of neutrino energies
  - Beams from 600MeV through 6 GeV
  - Tells us which channels are accessible
  - Neutrino and Antineutrino
  - ν_e and ν_μ both, ideally!



ν_μ Fluxes Available

- T2K
  - Off Axis: 700MeV narrow band beam
  - On axis: 1 GeV broad band beam
- Booster Neutrino Beam
  - 1GeV, broad band
- NuMI
  - On axis: 3, 6 GeV broad band beams
  - Off axis: 2 GeV beam



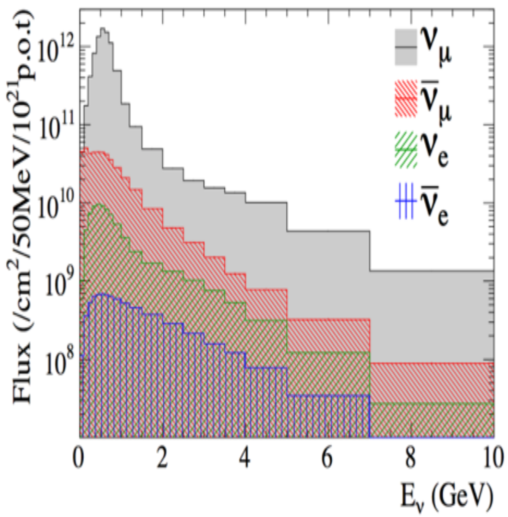
Plot adapted from P. Rodrigues, WINP

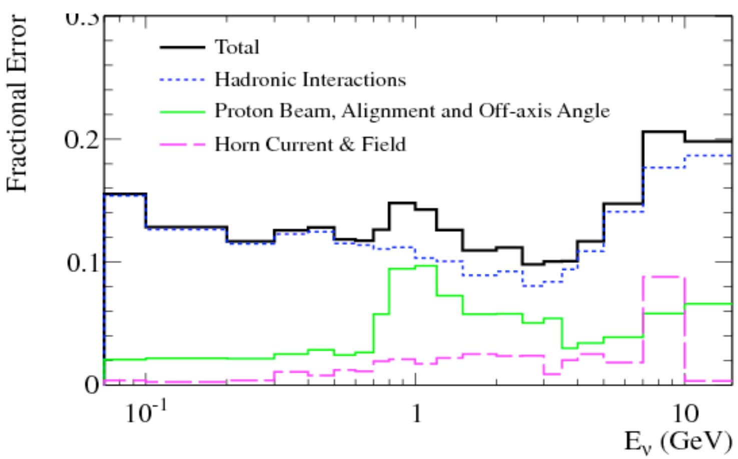
One limit to precision: Fluxes and their uncertainties

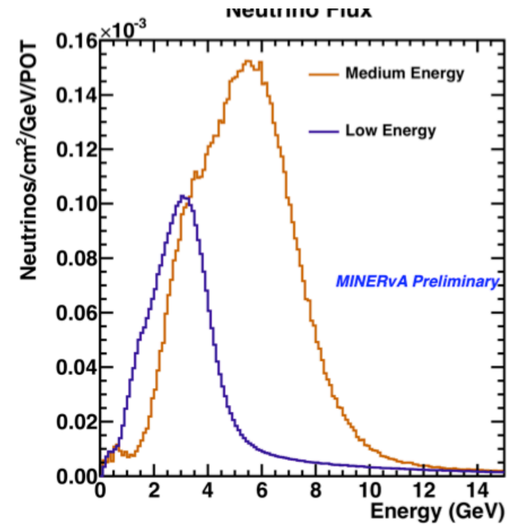
- T2K off Axis
- NuMI On Axis

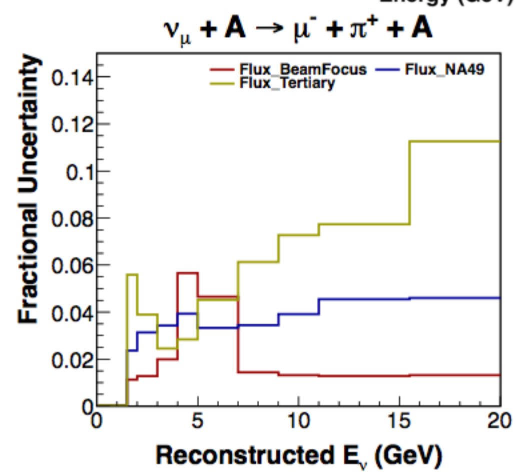
M. Wascko, Fermilab JETP Nov. 2014

Near detector flux









A. Higuera, Fermilab W&C Aug. 2014

Flux uncertainties on all species: BNB study

- Tables from determination of Booster Neutrino Beam flux uncertainties: (PRD 79 (2009) 072002)
- Note that the ν_e flux uncertainties are slightly smaller than the corresponding ν_μ flux uncertainties
- Incorporate results from HARP, dedicated hadron production experiment

ν

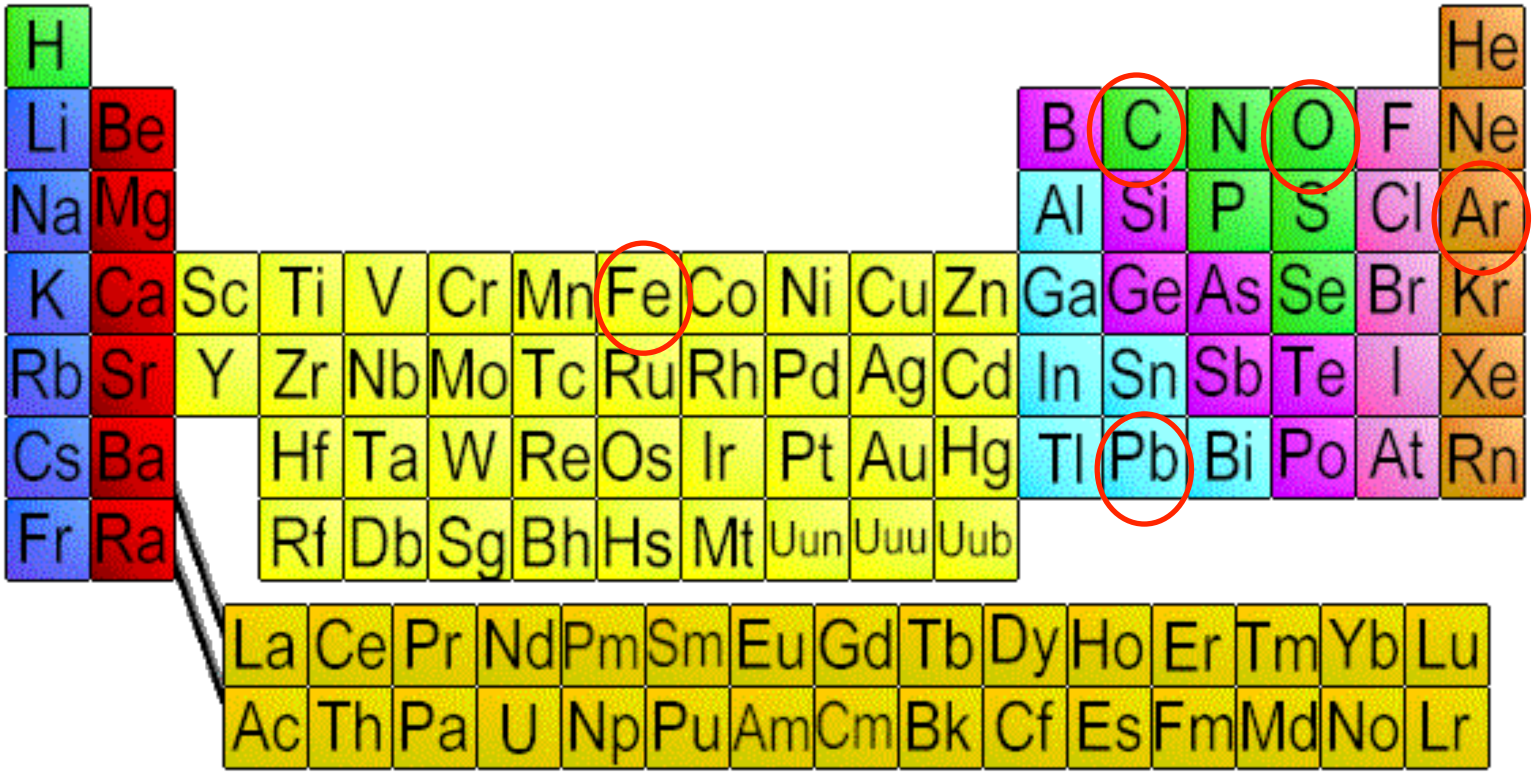
Source of Uncertainty	ν_μ	ν_e
Proton delivery	2.0%	2.0%
Proton optics	1.0%	1.0%
π^+ production	14.7%	9.3%
π^- production	0.0%	0.0%
K^+ production	0.9%	11.5%
K^0 production	0.0%	2.1%
Horn field	2.2%	0.6%
Nucleon cross sections	2.8%	3.3%
Pion cross sections	1.2%	0.8%

$\overline{\nu}$

Source of Uncertainty	$\overline{\nu}_\mu$	$\overline{\nu}_e$
Proton delivery	2.0%	2.0%
Proton optics	1.0%	1.0%
π^+ production	0.1%	0.1%
π^- production	17.5%	13.6%
K^+ production	0.0%	0.4%
K^0 production	0.0%	3.9%
Horn field	1.0%	1.5%
Nucleon cross sections	2.1%	2.5%
Pion cross sections	1.2%	1.5%

Testing Models: Broad Range of nuclei

- Important: even if far detector is one nucleus, want to get nuclear effect models right so need to test several nuclei



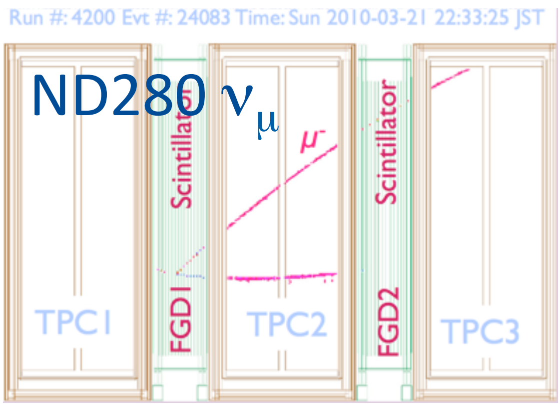
Another precision limit: the number of nuclei measured

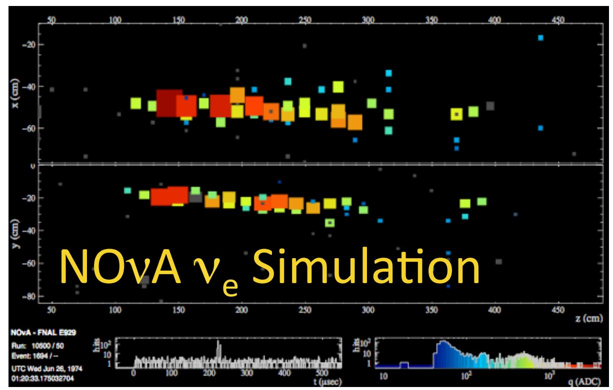
Other requirements for precision tests of models

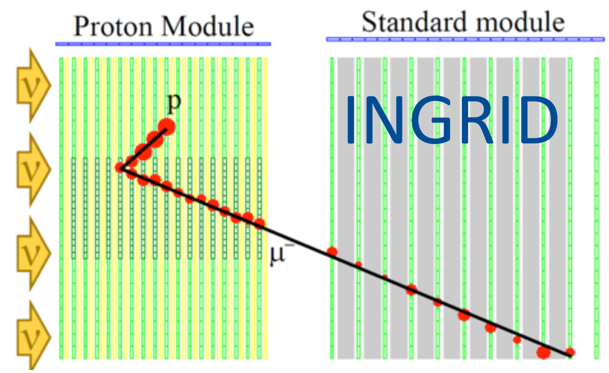
- Detector Capability
  - Could define as proton tracking threshold?
- Different capabilities mean we have to be that much more careful about how we define signal channel
- Move to "final state description" instead of process (CC 0π, instead of CCQE, for example)
- New Capabilities mean that we can compare hadron side of reaction with lepton side of reaction (see MINERvA ν_μ CCQE results)

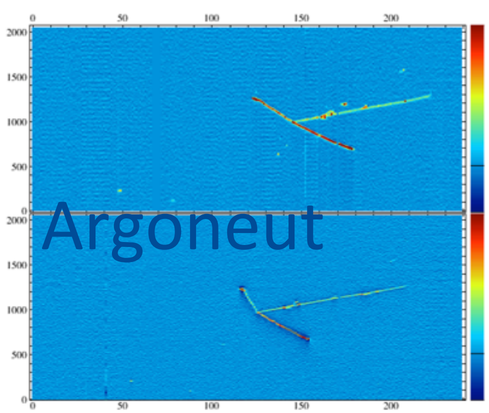
7 ways of looking at Neutrino Interactions

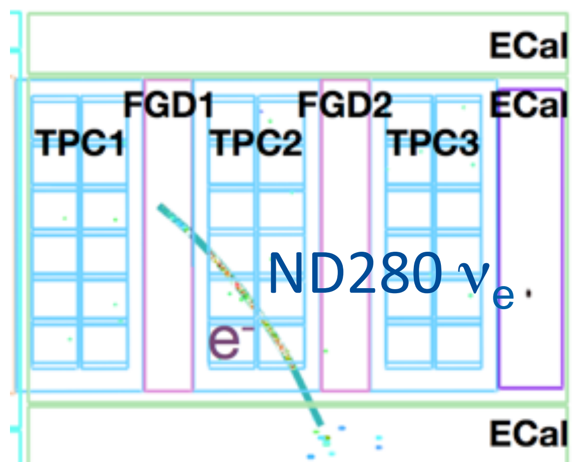
- All different levels of signal and vertex energy identification

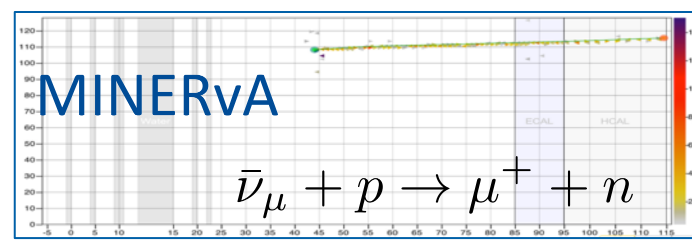


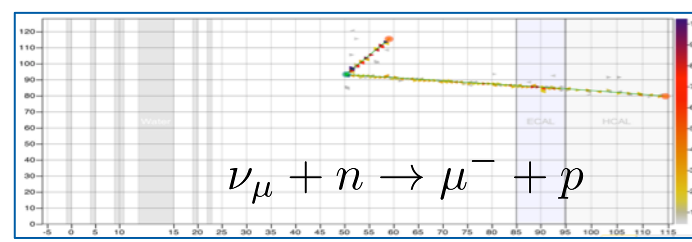












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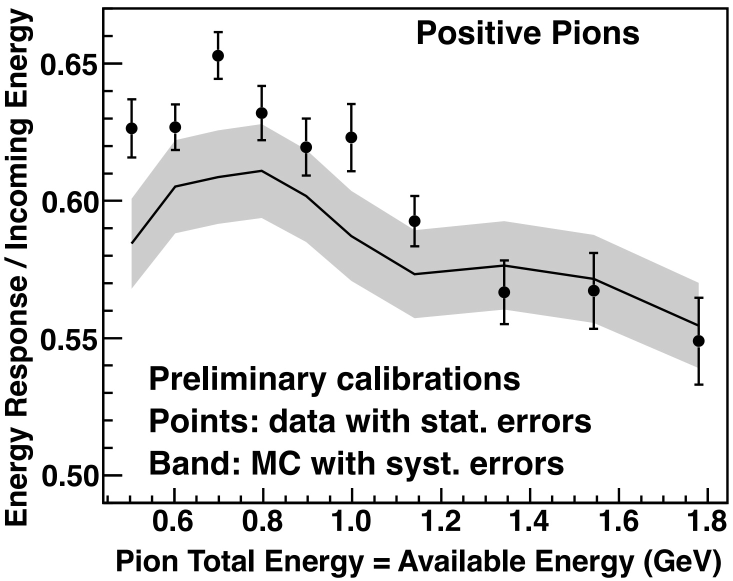
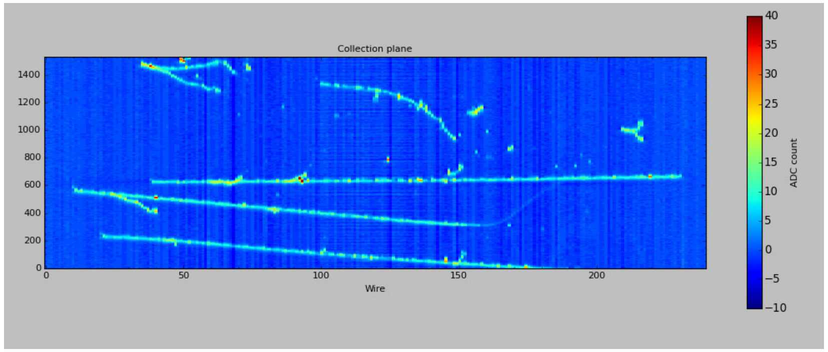
Limits of Precision from understanding detector

- Test beam programs are important components for cross-section measurements
  - MINERvA has low and medium energy test beam data ranging from 0.4 to 8GeV
- Typical total beam energy uncertainties: 3-4%



L. Aliaga et al, NIM A743 (2014)

- Event display from LAriAT from earlier this year: incoming pions on Argon
  - Taking data in low energy beam at FTBF: ~0.4-2GeV



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Current ν_μ Scoresheet

Energy/ Target	700MeV	1GeV	2GeV	3GeV	6GeV
C				MINERvA	MINERvA
CH_2		MiniBooNE			
CH	ND280	INGRID	NovA	MINERvA	MINERvA
H_2O	ND280			MINERvA	
Ar		MicroBooNE		Argoneut	
Fe		INGRID		MINERvA, MINOS	MINERvA, MINOS+
Pb				MINERvA	MINERvA

- This represents data already taken to date

ν_μ Process Scoresheet (Results)

Energy/ Target	700MeV	1GeV	2GeV	3GeV	6GeV
CH_2		CCQE, π production			
CH	CCQE	CCQE		CCQE, π prod.	
H_2O					
Ar				CCINC, Coherent, CC-no π	
Fe		CCINCL Ratio		CCQE, π prod, coherent, CCINCL ratio	
Pb				CCINCL ratio	

- This is a great start, but there are many other channels that can be probed with these data sets

Current anti-ν_μ Scoresheet

Energy/ Target	700MeV	1GeV	2GeV	3GeV	6GeV
C				MINERvA	MINERvA
CH_2		MiniBooNE			
CH	ND280	INGRID		MINERvA	
H_2O	ND280			Argoneut	
Ar					
Fe		INGRID		MINERvA, MINOS	
Pb				MINERvA	

- This represents data already taken to date

Anti-ν_μ Process Scoresheet (Results)

Energy/ Target	700MeV	1GeV	2GeV	3GeV	6GeV
CH_2		CCQE, π production			
CH				CCQE, π prod.	
H_2O					
Ar				CCINC, Coherent,	
Fe					
Pb					

- Many analyses still to come!

ν_e Process Scoresheet (Results)

Energy/ Target	700MeV	1GeV	2GeV	3GeV	6GeV
CH_2					
CH	CCINCL			CCQE (Wolcott)	
H_2O					
Ar					
Fe					
Pb					

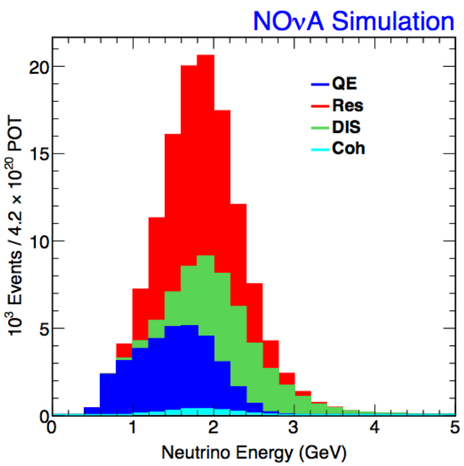
- Should not forget about these channels

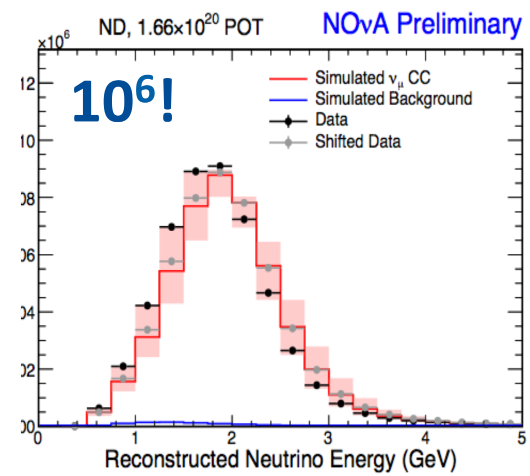
What is next?

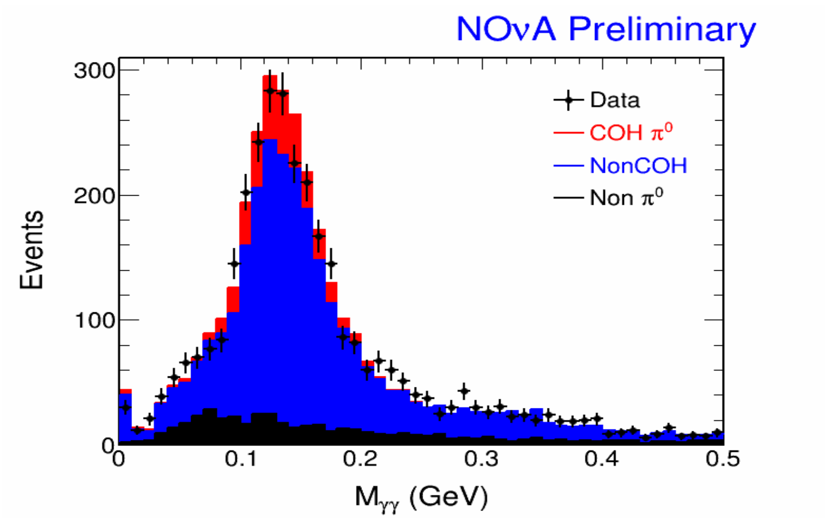
- Need to keep extracting results from current data sets
  - More handles on CCQE
  - CCQE ratios across different nuclei
  - New look at CCQE and pion production with Argon w/ MicroBooNE
  - What other clues are there on pion production?
  - Inclusive Ratio for different nuclei Improvements
    - Looking at DIS ratios at MINERvA
    - Antineutrino CC Inclusive ratios at MINERvA

Upcoming results from NOvA

- Analyses Underway (J. Paley, NuFact15)
  - ν_μ CC
  - ν_e + A
  - ν + e (flux constraint)
  - Coherent π^0
- Dominant ν_e + A Systematics
  - Flux (21%)
  - Energy scale (10-15%)
  - Improve both with MIPP and supporting ν_μ analyses







Upcoming results from T2K

- On Axis
  - QE two-track versus QE-like
    - Multi-nucleon searches
  - QE double differential
  - Charged pion double differential
  - Neutral Pions
  - Coherent charged (neutral?)
  - More ν_e cross sections
  - Nuclear Ratios (w/$H_2$0, Pb, CH) for model comparisons
  - Pion multiplicities

- On Axis
  - Energy dependent ν_μ CC inclusive on Fe
  - ν_μ CC Coherent pion production on C
  - ν_μ CC 0π differential on C

From K. Mahn

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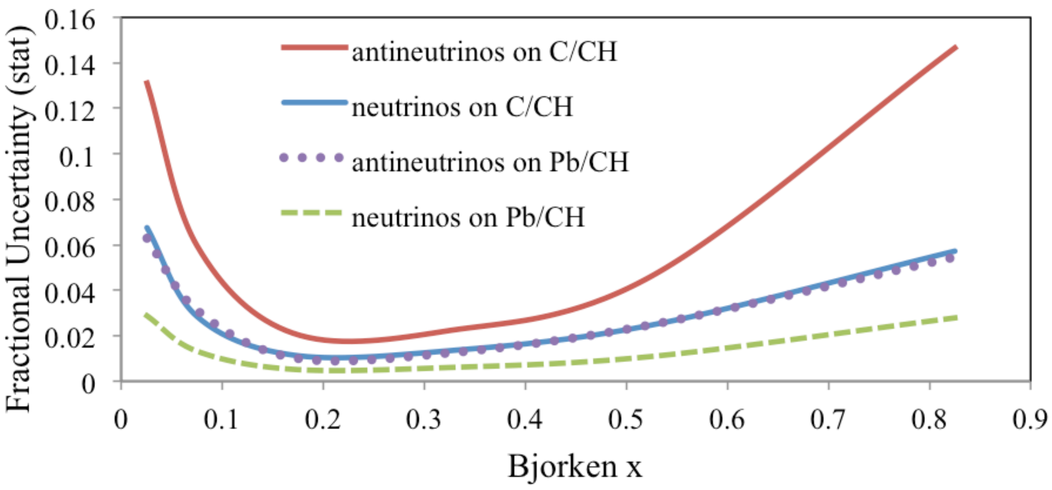
Upcoming results from MINERvA

- ν_e CCQE cross sections (Ghosh)
- Nuclear target ratios for DIS events (Bravar)
- ν_μ CCQE double differential (Carneiro)
- CCQE on Fe, Pb, C compared to CH in Low Energy Beam
- Medium Energy results will feature much higher statistics
  - Higher flux and cross section, higher numbers of protons on target collected
  - Exclusive channel ratio results for Fe, Pb, C, compared to CH



  - Chance to look at nuclear effects in DIS at few per cent level!

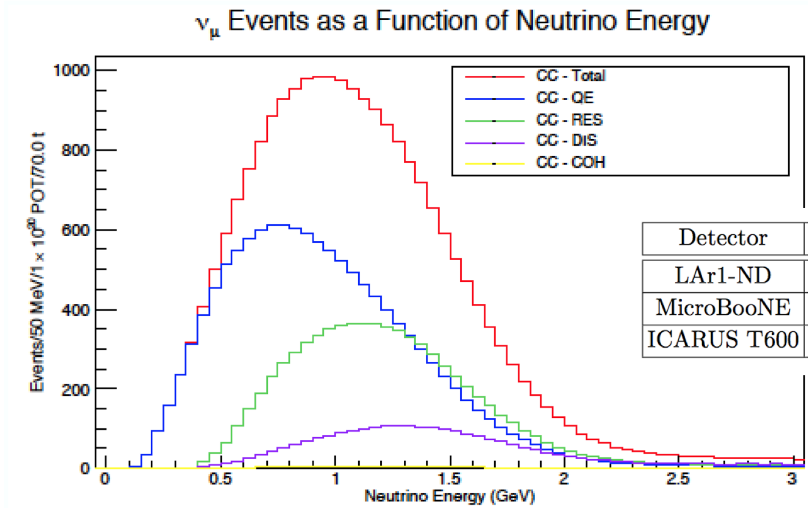
DH, FNAL PAC 6/15

Where are we lacking statistical precision we need?

- Need more events on Argon
  - MicroBooNE taking first statistics at 1GeV
  - 3GeV and above Neutrinos on Agron: handfuls of events recorded, need more!
- Nuclear Target Inclusive and pion cross section ratios at MINERvA: needs Medium Energy antineutrino data
- ν_e data sets in their infancy: individual channels hard to isolate even in cross section detectors

Next Step for 1GeV LAr Measurements

- 3 detectors, statistics at 5M!
- Mix of CCQE, Resonance
- Events below for 6.6E20POT
- LAr1-ND: 3M CCQE, >1M pion production events
- All detectors have fine granularity

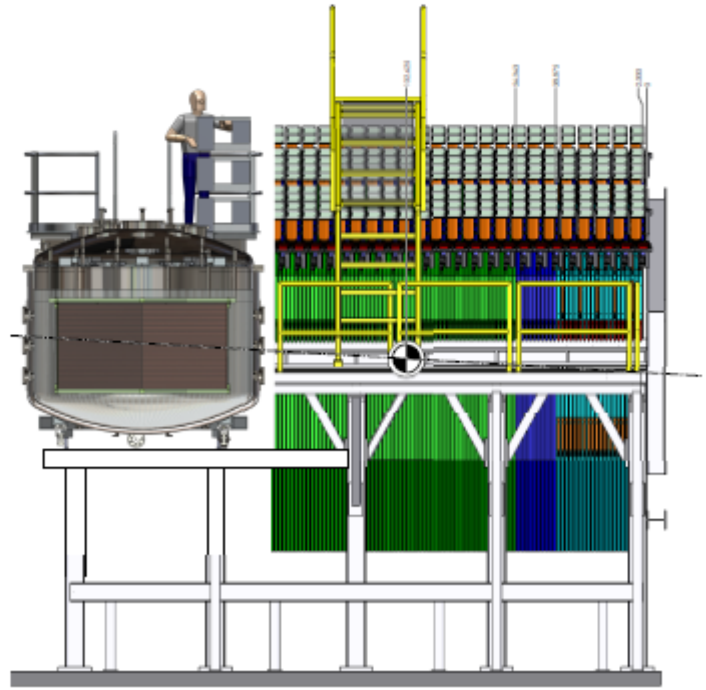


F. Cavanna, WINP

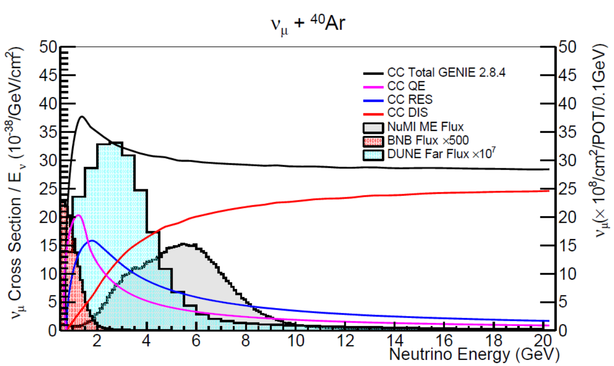
Detector	Distance	Fiducial Mass	CC ν_μ events	CC ν_e events
MicroBooNE	470m	61t	122k	800
LAr1-ND	110m	112t	5.2M	38k
ICARUS	600m	476t	550k	2k

Next step for 3-6GeV LAr precision: CAPTAIN MINERvA

- Install the CAPTAIN detector in MINERvA to study neutrino-argon interactions in the medium-energy NuMI beam
- CAPTAIN-MINERvA can measure cross section ratios (i.e., argon to carbon)
  - More stringent tests of the models can be performed with ratios due to cancellation of large systematic uncertainties such as the neutrino flux
- Stage I approval from Fermilab Director



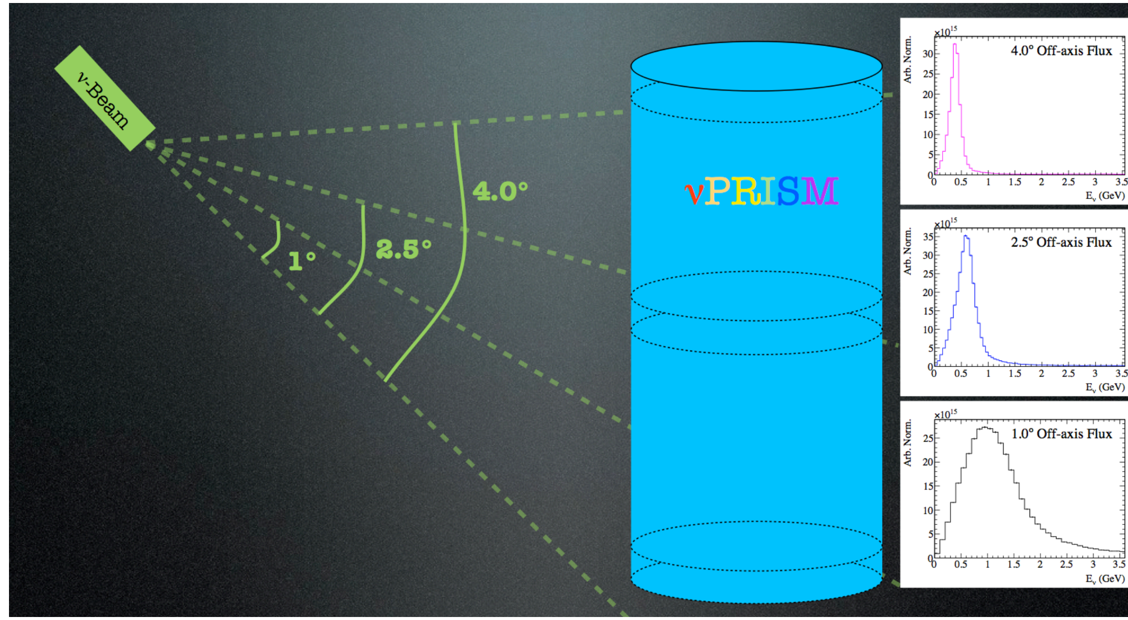
@6x1020 POT	Events with reco. μ	Events with reco.μ + chg
CCQE-like	900k	800k
CC $1\pi^{\pm}$	2000k	1000k
CC $1\pi^0$	1600k	600k

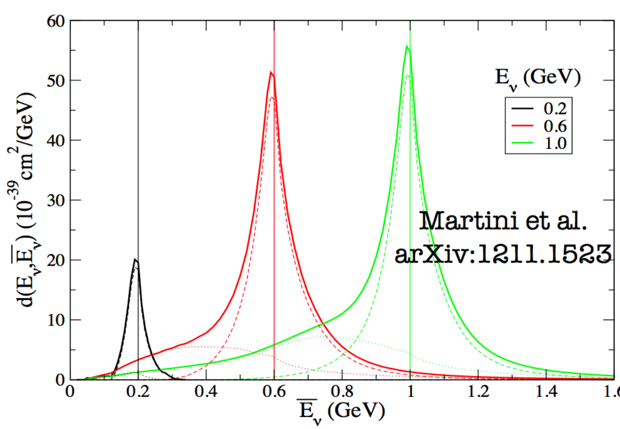


L. Whitehead, FNAL PAC 6/15

Getting to a MonoChromatic Neutrino Beams

- NUPRISM:
  - Take advantage of 2-body decay kinematics to “create” monochromatic energy beams
  - Not for the faint of heart, will need a lot of statistics to do subtractions from different locations
  - Best chance at directly quantifying this picture
- What about other targets?





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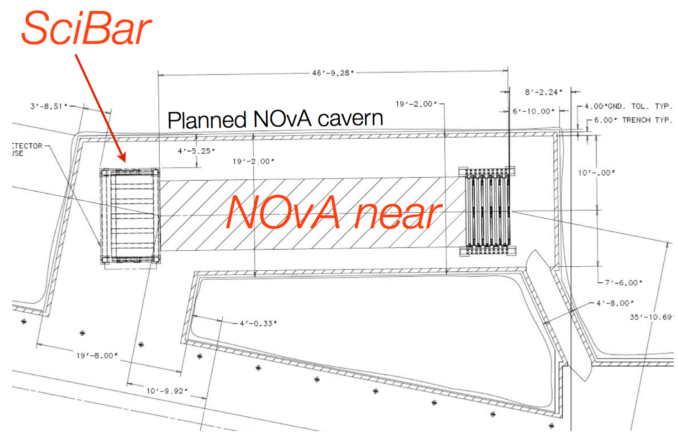
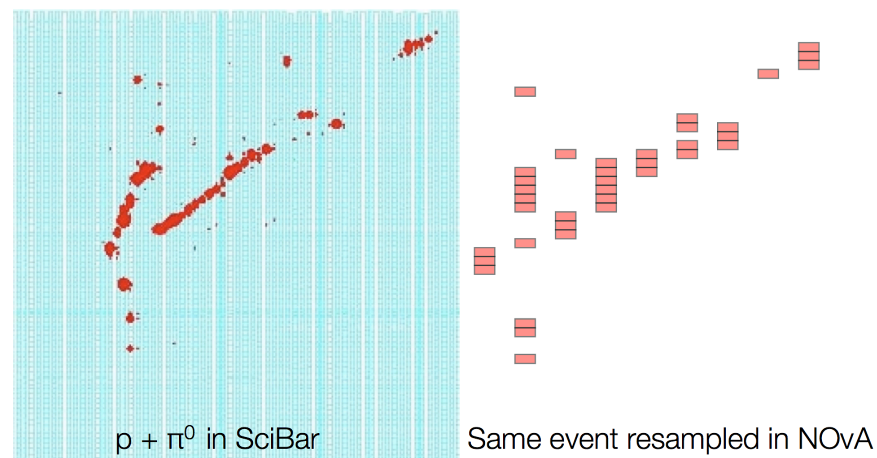
SciNOvA

- Add SciBar in front of NOvA's Near Detector
- In situ check of backgrounds to ne search in NOvA's FD
- Would also be a great way to see energy dependence of CC and NC interactions by comparing to MINERvA events
  - Fluxes very correlated
  - Nucleus is the same





M. Messier, 2011 FNAL PAC talk

Conclusions

- We need to harvest the impressive data that is already recorded
  - MINERvA Medium Energy program
  - NOvA
  - T2K ND280 and INGRID
- Need to get good statistics in anti-neutrino mode and harvest that data as well!
- Many plans for improved cross section measurements
  - MicroBooNE followed by SBND
- Short term future projects seeking funding
  - CAPTAIN MINERvA, SciNOvA
- Longer term program: NuPRISM, WAGASCI, TITUS

FINAL Scoresheet including future prospects

Energy/ Target	700MeV	1GeV	2GeV	3GeV	6GeV
C				MINERvA	MINERvA
CH_2		MiniBooNE			
CH	ND280	INGRID	NovA	MINERvA	MINERvA
H_2O	ND280, NUPRISM	NUPRISM		MINERvA	
Ar		MicroBooNE, SBND		CAPTAIN-MINERvA	CAPTAIN-MINERvA
Fe		INGRID		MINERvA, MINOS	MINERvA, MINOS+
Pb				MINERvA	MINERvA

Now picture 3-4 interaction channels per box, times 2 (ν + anti-ν)

We have a great opportunity here for a much more complete picture